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Silicon oxinitride : a material for compact waveguide device

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Abstract In recent years growing attention has been paid to silicon oxynitride (SiO_xN_y or SiON in short) as a potential material for Compact integrated optical waveguide devices due to its excellent optical properties such as wide range of refractive index between 1 45 (SiO_2) – 2 0 (Si_3N_4) The reduction of coupling length of directional coupler with small gap using high index contrast waveguide with SiON Core and SiO_2 cladding has been studied The experimental results of the coupler power versus coupling length of the directional couplers are shown and the corresponding beat legnth is 65μm Finally the wavelength multiplexing / demultiplexing using compact directional couplers is discussed

Keywords Directional coupler Silicon oxinitride (SiON), wavelength multiplexer / demultiplexer

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1. Introduction

Recently optical network has been required to fulfil the skyrocketing demand of bandwidth in present day's high speed communication systems Wavelength division multiplexing [1,3], optical matrix switches [2] and EDFA gain equalizer [4] are essential to realize these communication systems These devices are fabricated using integrated optical circuit technology One of the basic components of these devices is directional coupler Traditionally, directional couplers using $LiNbO_3$and GeO_2-SiO_2 material require relatively large area due to their waveguides having weakly guided where the Δn is order of 0 5%–2% and coupling length – 2mm–6mm [1,2], [5,6] However, the design and fabrication of the compact waveguide has become essential in photonic integrated circuit to achieve high density integration. In recent years, silicon oxynitride ($Si_xO_yN_z$ or SiON for short) has become potential material for fabrication of compact planar waveguide devices [3,4,7] It is reported that conversion of a silicon nitride to SiON by introducing oxygen improves thermal stability, cracking resistance and decreases thermal stress [7] To accommodate more number of components in a single chip, directional coupler (DC) with small gap (*h*) [8] are considered with higher value of Δn due to its strongly guiding property

In this paper, SiON/SiO_2 waveguide material is used in design and fabrication of compact integrated optical devices The reduction of coupling length of directional coupler with small gap using high index contrast waveguide has been studied. The experimental results of the cross state power *versus* coupling length of the devices are shown. Finally, the wavelength multiplexing / demultiplexing using directional couplers is discussed.

2. Motivation of works

SiON has been attracted for the material of compact integrated planar waveguide device mainly due to wide variation of refractive index between 1.45 and 2, where refractive index of SiO_2 and Si_3N_4 are ~ 1.45 and 1.9793 respectively at wavelength λ = 1.55 μm [7] It has been demonstrated by previous authors [7] that the refractive index of SiON increases with increase of more fraction of Si_3N_4 So, the index of SiON varying between1.45 and 2 can be approximated with linear expression as

$$n_{SiON} = X_{SiO_2}\, n_{SiO_2} + X_{Si_3N_4} . n_{Si_3O_4} \tag{1}$$

$$X_{SiO_2} + X_{Si_3N_4} = 1 \tag{2}$$

where, X_{SiO_2} and $X_{Si_3N_4}$ are mole fractions of silicon dioxide (SiO_2) and silicon nitride (Si_3N_4) The waveguides fabricated by SiON material have the following structure · silicon is used as a substrate, SiO_2 layer thermally grown on it is acted as a buffer layer for the SiON guiding film on top of which SiO_2 is deposited to provide symmetric structure Due to wide refractive index variation of SiON material (obtained using the equations (1) and (2)), it is possible to fabricate high index contrast waveguides using the above structure Further, this attention has also been motivated by its excellent optical properties such as low absorption losses in the visible and near infrared region. SiON combines the dielectric properties of SiO_2 together with good chemical inertness and low permeability of Si_3N_4

In comparison to other high index waveguide material such as InP/ GaAsInP, SiO_2/ SiON material is low cost and uses well established standard silicon integrated circuit processing for fabrication of waveguide device.

3. Compact directional coupler

One of the main components of waveguide device is directional coupler. Figure 1 shows a symmetric directional coupler consisting of two identical waveguides of core width *w* and thickness *t* placed in close proximity to each other in coupling region of length *L* and two transition region of length L_T. The input power P_1 is incident in waveguide-1 and then the output powers P_3 and P_4 can be obtained as a cross state and bar state respectively. The core refractive index of waveguide is n_2. The index between the spacing of two waveguides in coupling region is assumed to be n_3 with the gap *h*. The refractive index of surrounding medium of the waveguide cores is n_1. When the light is launched in to the access waveguide port-1 of DC, it excites equally the even and odd super modes which then propagate with propagation constant, β_e and β_o respectively. At every point along the DC, the field distribution will be a linear superposition of these modes.

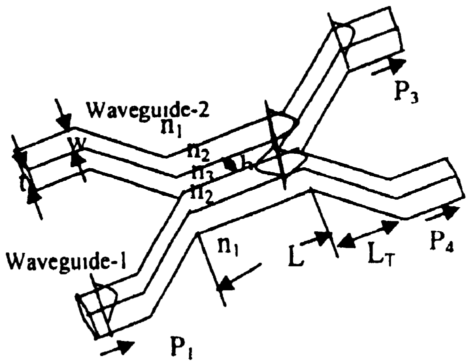


Figure 1. Directional coupler of core width w and thickness t with small gap h in coupling zone (L)

From the coupled mode theory [11] the output power can be written as,

$$P_4/P_1 = \cos^2[kz] \tag{3}$$

$$P_3/P_1 = \sin^2[kz] \tag{4}$$

where, coupling coefficient, $k = (\beta_e - \beta_0)/2$. The coupling coefficient k in terms of h can be obtained from Mercuse's equation [4] considering slab directional coupler (2D model) as

$$k = C(\Delta n, w, \lambda)\, e^{\,h\gamma_3} \tag{5}$$

where, $\gamma_3 = \sqrt{\beta^2 - n_3^2 k_0^2}$, $C(\Delta n, w, \lambda)$ depends on waveguide parameters such as index contrast (Δn), core width (w) and wavelength (λ) and it is independent of spacing, h between two waveguides in coupling region. At z = 0, these fields cancel each other at the waveguide-2 and power will be confined fully in waveguide-1. Since both the compound modes have slightly different propagation constants, their relative phase change will reverse at a distance, $z = L_\pi$, where, L_π = beat length which is given by

$$L_\pi = \frac{\pi}{2k}. \tag{6}$$

Considering the dispersion equation for TE mode, we have determined β in calculating L_π. Keeping $n_1 = n_3$ = 1.447 and V ~ 2.4, Figure 2 shows the variation of L_π with index contrast Δn for h = 0.2 µm, 0.5 µm, 0.8 µm and 1.1 µm obtained using the equation (5) and (6). For TM mode, L_π decreases by 1% in comparison to TE mode. The experimental results demonstrated by previous authors using SiO_2/SiON [3] technologies are shown in the figure, proving almost same with the theoretical values. The rate of decrease of L_π

with respect to Δn, $\partial L_\pi/\partial(\Delta n)$ is almost same for all h values mentioned in the figure but $\partial L_\pi/\partial(\Delta n)$ for $\Delta n \geq 5\%$ is less than that for $\Delta n < 5\%$ at a fixed value of h. So L_π decreases slowly with Δn for $\Delta n \geq 5\%$. The figure also shows that as h decreases, the variation of L_π with Δn gets closer and closer. This variation at h = 0.5 μm is almost same with that at h < 0.5 μm. For compact directional coupler with h = 0.5 μm, we have chosen Δn = 5%.

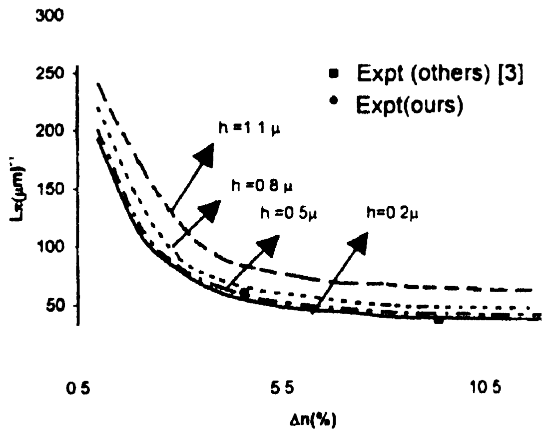


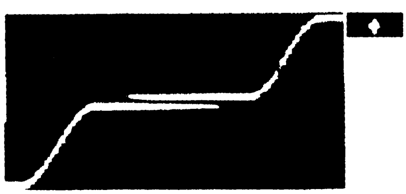
Figure 2. Variation of L_π with Δn for h = 0 2 μm, 0 5 μm, 0.8 μm and 1.1 μm for $n_1 = n_3$ = 1 45, V 2 4 and λ = 1 55 μm

In a DC, there are two branching region of length L_T branching region of DC consists of S-bend. The S-bend loss (dB) is expresed in terms of L_T as follows,

$$T_s = 4.343 L_T C_1' \exp(-C_2' L_T) \tag{7}$$

where, c'_1 and c'_2 are constants which are obtained from Mercuse's bending loss formula [11]. For T_s of 0.01 dB, L_T is obtained for $\Delta n = 5\%$ as 200 μm.

Figure 3(a) shows the light propagation in cross state of DC of coupling gap h = 0.5 μm, coupling length ~ 57 μm, w = 1.5 μm, core index ~ 1.5 and index contrast = 5% obtained using OptiBPM simulator. OptiBPM is a computer-aided design software tool enabling light wave propagation in optical waveguides using Beam propagation Method (BPM). Figure 3(b) shows cross state single mode output.



(a) (b)

Figure 3. Light propagation in DC with h = 0.5 μm, coupling length ~ 57 μm, w = 1.5 μm and index contrast = 5% . (a) Cross state (b) cross state single mode output.

4 Fabrication and result

We have fabricated passive DC of different values of L, for which we have chosen silicon wafer of thickness ~ 1 mm and diameter ~ 3 inches The surface of silicon wafer was flattened by mechanical polishing and cleaned in DI water and acetone with ultrasonic agitation

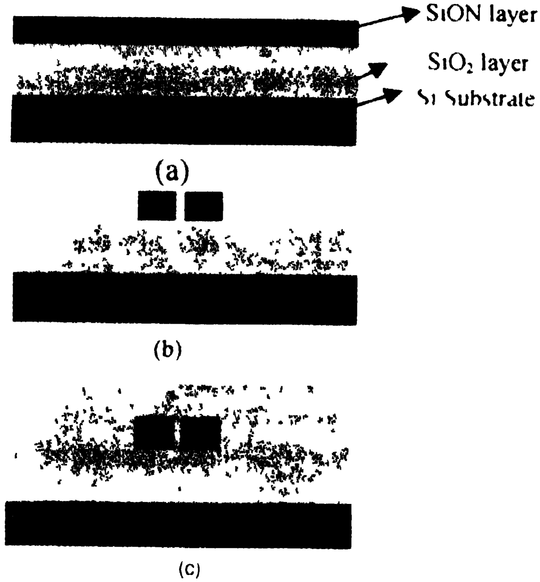


Figure 4 Fabrication steps of the DC (a) lower cladding (SiO) using wet oxidation method and guiding layer (SiON) obtained by PECVD (b) formation of cores using Mask and photolithography and RIE (c) formation of top cladding

The 5 5 µm thick lower cladding of SiO_2 with n_1 ~ 1 447 was made on the polished surface of the wafer using the wet oxidation process at the temperature of 1100 °C Then, 1 5 µm thick guiding layer of SiON with refractive index ~ 1 5 (Δn = 5%) was deposited on the SiO_2 layer with the reactant gases, silane, ammonia (NH_3), and nitrous oxide (N_2O) using plasma electron chemical vapour deposition (PECVD) system (model no Plasmalab 8510 C) at temperature 300 °C, pressure 0 3 Torr and RF power 120 watts with frequency 380kHz. The flow rates of silane, NH_3 and N_2O were maintained at ~ 180 sccm, 4 sccm and 200 sccm, respectively The refractive index and thickness of deposited layer was measured by the prism coupling technique using the Metricon 2010 apparatus Figure 4(a) shows the cross section of the deposited layers The required mask having gap h ~ 0 5 mm of DC of different lengths and standard photolithography technique were used to fabricate the pattern of the waveguides The core width of the waveguides of device was taken as w =1.5 µm and different L values were 30 µm, 65 µm, 100 µm, 130 µm and 190µm. For selective etching, 100 nm thick nichrome (N_i- Cr) was deposited on the top surface of the guiding layer using e-beam evaporation technique at vacuum of 5 × 10^{-6} torr. The 3D core structure was obtained by dry etching using reactive ion etching (RIE) system (model no · ANELVA 506 M) The reactant gases for the RIE system were

Ar^{++} CHF_3, and O_2 gases with the flow rates of 2 5sccm, 5sccm and 2 sccm, respectively The applied RF power for etching was 100 W with frequency, 13.56 MHZ and the etch rate was ~ 15 nm/min following the etching time for 1 5 μm thick SiON layer ~ 100 min Then, the metal on the top surface of the waveguide was removed by wet etching using NiCr TFN etchant Figure 4(b) shows the cross section of the coupling waveguide cores of DC After cleaning with acetone, the top cladding of 3 μm thick SiO_2 was made with Silane (180 sccm), and Nitrous Oxide (180 sccm) using PECVD method with the same process parameters as mentioned above Figure 4(c) shows the cross section of the top cladding and coupling waveguide cores of the device Figure 5 shows microphotograph of coupling region of one of the directional couplers

Figure 5 Microphotograph of coupling portion of DC

The cross state power measurement of the DC was performed using a stabilized laser diode of wavelength 1 55 μm and movable germanium detector which are butt coupled with device *via* optical fibers The detected power was amplified by the chopper stabilized transimpedance preamplifier A minimum detectable power of the order of 100 pW was obtained when the receiver was properly shielded The wave guide propagation losses are ~ 0 25 dB/cm and the fiber to chip loss per facet is < 1 3 dB Figure 6 shows experimental cross state power (P_3/P_1) of directional couplers with h ~ 0 5 μm and Δn = 5% The black dots represent the experimental points for the cross state power The dashed line in the figure represent the curves passing through the experimental points with minimum deviation The solid lines represent the theoretical curves obtained by using the equations (4) to (5) The theoretical and the experimental values of L_π are ~ 57 μm and 65 μm respectively The difference of these values may be due to the deviation of the designed device parameters such as w, L and Δn during fabrication The reduction of the experimental normalized peak output power (~ 0 95) is mainly the radiation loss occurring

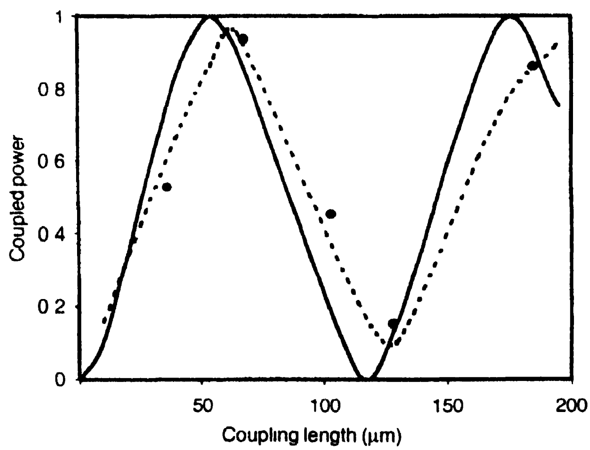


Figure 6. Cross state power *vs* coupling length for Dc with l = 0 5 μm and Δn = 5% (solid line- theoretical and dashed in-experimental)

in the bending portion of the waveguide. The black dot in the Figure 2 represents experimental value of L_π almost matching with theoretical value.

5. Wavelength multiplexer/demultiplexer using DC

We know that wavelength multiplexer/demultiplexer can be developed using a DC with small coupling gap [3]. For two wavelengths λ_1 and λ_2, even and odd mode propagation constants of the coupler are $\beta_e^{\lambda_1}$, $\beta_0^{\lambda_1}$, $\beta_e^{\lambda_2}$ and $\beta_0^{\lambda_2}$ respectively and the required coupling length can be approximately written as,

$$L_c = \frac{\pi}{\Delta\beta|_{\lambda 1} - \Delta\beta|_{\lambda 2}} \tag{8}$$

where, $\Delta\beta_{\lambda 1} = \left(\beta_e^{\lambda_1} - \beta_0^{\lambda_1}\right)$, $\Delta\beta_{|\lambda 2} = \left(\beta_e^{\lambda_2} - \beta_0^{\lambda_2}\right)$. These propagation constants are determined by using effective index method [10] and where $\beta_e^{\lambda_1}$, $\beta_0^{\lambda_1}$, $\beta_e^{\lambda_2}$ and β_0^{λ} are ~ 6 0704, 6.05201 and 5.98977 $(\mu m)^{-1}$, respectively for the wavelengths $\lambda_1 - 1\ 52 \mu m$ and $\lambda_2\ 1\ 54\ \mu m$, of the coupler with Δn = 5% L_c is calculated as 5.92 mm Similarly for a four channel multiplexer/demultiplexer with Δn = 5%, requiring three directional couplers-having two couplers of the same coupling length L_c and other one of $2L_c$ and considering $\lambda_1 - 1\ 52\ \mu m$, $\lambda_2 = 1\ 54\ \mu m$, $\lambda_3 = 1.56\ \mu m$ and $\lambda_4 = 1\ 58\ \mu m$, the device length can be obtained approximately as ~ 8 mm which is about two times less than that of the TMI coupler with Δn = 0.6%, using Ti:$LiNbO_3$ [1].

6. Conclusion

In this paper, compact directional coupler having small gap of 0.5 μm using SiON/ SiO_2 waveguide with Δn of 5% is demonstrated and its corresponding beat length is ~ 65 μm The wavelength multiplexing /demultiplexing using the compact directional coupler is discussed.

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